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Boundary-Layer and Turbulence Intensity Measurements in a Shock Wave/Boundary-Layer Interaction

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Nomenclature

e_f^2 = root mean square voltage
f = frequency
H = compressible shape parameter, $=\delta^*/\theta$
ℓ_s = length of separated flow region
M_{pk} = peak Mach number
n = frequency parameter, $=fy/U_\infty$
Tu_∞ = freestream turbulence intensity, $=\tilde{u}/U_\infty$
Tu = turbulence intensity in boundary layer
u = velocity
$\tilde{u}$ = root mean square velocity fluctuation
U_∞ = freestream velocity
U_{BS} = freestream velocity before shock
y = vertical ordinate
δ = boundary-layer thickness

Subscripts

1 = conditions before shock at station 1
2 = conditions at the trailing edge of the model

Introduction

PREVIOUS work by the authors has shown that attached turbulent boundary layers at zero pressure gradient are sensitive to the freestream turbulence.[1] The effect of freestream turbulence on the boundary layer at positive pressure gradients is very little understood.[2] An investigation of the influence of freestream turbulence on shock induced separation is presented in this Note.

Experiments

Experiments were performed in a 10-cm^2 transonic suckdown tunnel with a slotted floor.[1] The model was a roof-mounted half-biconvex aerofoil (9 deg thick). During the tests the peak Mach number was $M_{pk}=1.44$ before the shock. This resulted in a flow separation at the foot of the shock followed by reattachment on the tunnel roof downstream of the trailing edge of the model (Fig. 1). Boundary-layer and hot-wire traverses were made at stations just upstream of the shock and in the separated region at the trailing edge. The freestream turbulence was varied by monoplane grids, the details of which are given in Ref. 1. The freestream turbulence was within the range 0.3-6.0%.

Results and Discussions

Velocity profiles upstream of the shock and downstream at the trailing edge of the model are shown in Fig. 1. The profiles shown here are for a shock Mach number of 1.44 and freestream turbulence levels of $Tu_\infty=0.34$ and 3.68%. The profiles are normalized with respect to the corresponding upstream boundary-layer thickness δ_1. The boundary layer upstream of the shock is in a region of negative pressure gradient and has a "full" velocity profile. Increase in Tu_∞ results in a fuller velocity profile. The velocity profile at the trailing edge shows that the flow is completely separated. It appears that the separated layer becomes thinner with larger values of Tu_∞. This is obviously due to increase in momentum exchange between the freestream and the separated layer at larger values of Tu_∞. Thus, there is an influence of the freestream turbulence and the boundary layer in the entire region of the shock/boundary-layer interaction.

Figure 2 shows for various freestream turbulence levels the boundary-layer integral properties in the separated layer at the trailing edge expressed as a fraction of the corresponding properties upstream of the shock. It is observed that for $Tu_\infty<2\%$, the displacement thickness ratio δ_2^*/δ_1^* and the shape factor ratio H_2/H_1 are very sensitive to Tu_∞ but the momentum thickness ratio θ_2/θ_1 is not sensitive to Tu_∞. The values obtained here at low Tu_∞ are comparable to those measured by Kooi[3] and Delery[4] at identical Mach number and at similar locations. Kooi measurements were performed on a flat plate with a shock generator, whereas those of Delery were performed on an aerofoil. The freestream turbulence was not measured in both cases.

The longitudinal turbulence intensity distribution at the two locations and for $Tu_\infty=0.34$ and 3.68% are shown in Fig. 3. The turbulence fluctuation levels are normalized with respect to the corresponding freestream velocities upstream of the shock. The turbulence intensity profiles show a strong interaction between the freestream turbulence and the boundary-layer turbulence in the outer region of the attached boundary layer and the separated layer. The peak levels of turbulence in the attached boundary layer near the shock are close to the measured peak values on an attached boundary layer at zero pressure gradient. However, the turbulence is likely to have become anti-isotropic upstream of the shock.

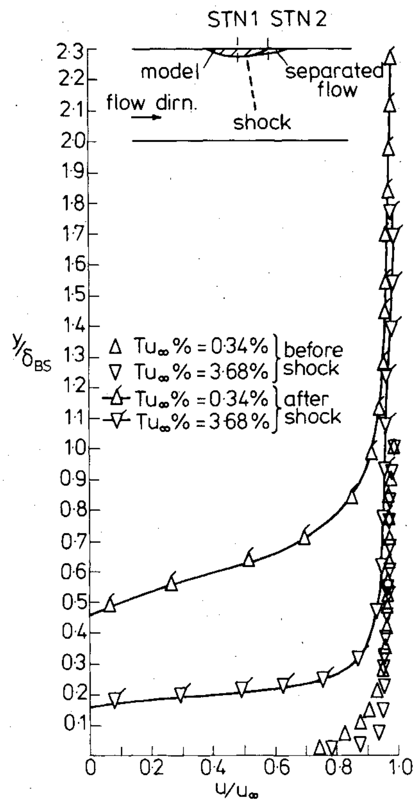

Fig. 1 Velocity profiles.

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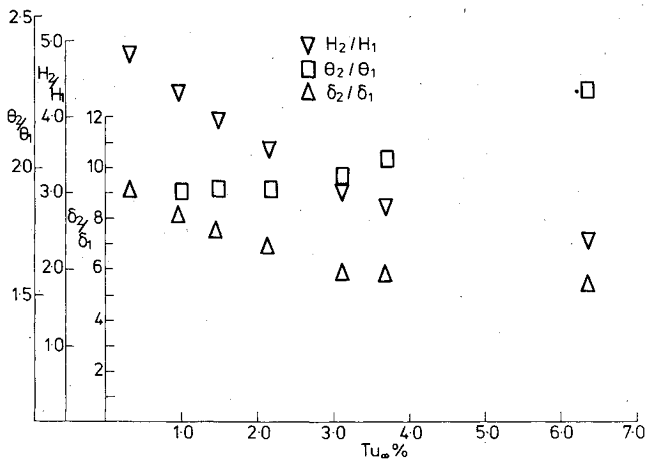

Fig. 2 Variation of compressible shape parameter ratios, momentum thickness ratio, and boundary-layer thickness ratio, across the shock, with freestream turbulence level.

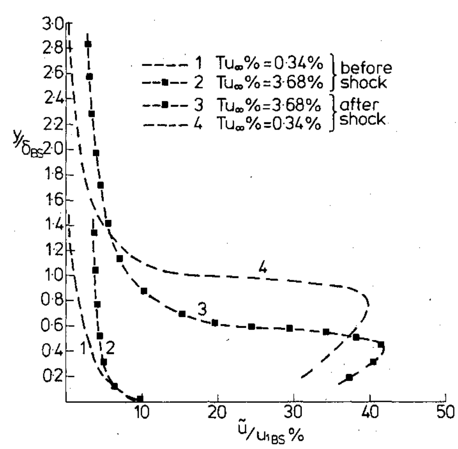

Fig. 3 Turbulence profiles.

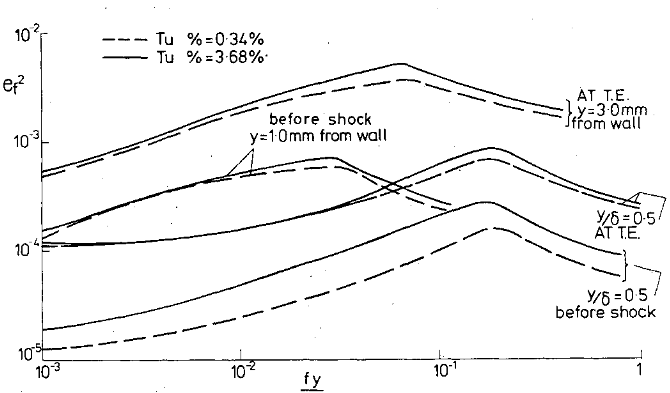

Fig. 4 Turbulence spectra.

The freestream turbulence has no noticeable effect on the peak turbulence levels in the separated layer, indicating that the generated level of turbulence in this region is not dependent upon Tu_∞. However, the distribution of turbulence in the separated layer is governed by Tu_∞. Typically, change in Tu_∞ from 0.34 to 3.68% results in a change in y/δ_l values for the peak turbulence level from 0.8 to 0.4.

The spectra of turbulence in the boundary layer for the given test conditions are shown in Fig. 4. In the outer region of the boundary layer ($y/\delta_l = 0.5$) there is a similarity of spectra between the attached boundary layer upstream of the shock and the separated layer at the trailing-edge location.

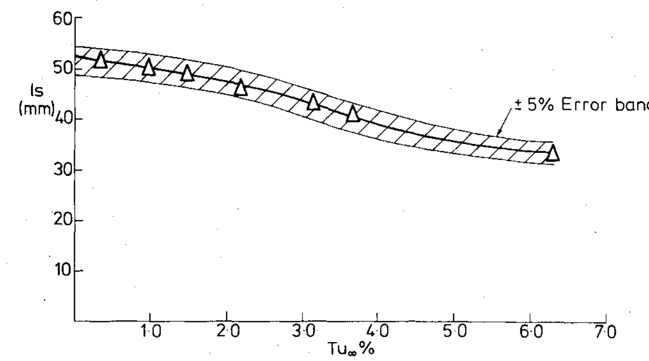

Fig. 5 Effect of freestream turbulence on separated flow length.

The nature of the spectra is rather insensitive to Tu_∞. The Strouhal number or frequency parameter n for the peak value of turbulence is approximately 0.2 and correlates well at a constant value of y/δ_l. It has been suggested by Bradshaw[5] that for the outer region of the boundary layer ($y/\delta_l > 0.2$) the turbulence is governed by the eddies many boundary-layer thicknesses upstream and there is not a strong function of local conditions.

Close to the wall, the values of n for the peak turbulence level is not the same for both types of boundary layers; correlation with Tu_∞ is obtained when correlated at constant values of y.

The length of separation is affected by the freestream turbulence. It is shown in Fig. 5 that an increase in Tu_∞ results in a decrease in separation length ℓ_s. The decrease in ℓ_s could be attributed to the increase in boundary-layer thickness associated with the increase in Tu_∞ upstream of separation, but only partially, as shown in Ref. 6. It appears that the rehabilitation of the boundary layer is enhanced by the increase in Tu_∞. This could explain the behavior of turbulence within the separated layer with the increase in Tu_∞ (Fig. 3). It has been shown that the peak levels in Tu occur close to the wall as the reattachment is approached. The turbulence traverses at the large value of Tu_∞ corresponds to a station nearer the reattachment when compared with traverses at the low Tu_∞ level.

Thus, it can be concluded that the boundary-layer behavior in a region of shock induced separation is sensitive to the freestream turbulence. The influence of freestream turbulence on the wall pressure fluctuations for this case is currently under investigation.

Acknowledgment

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